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Economic CO₂ network optimization model COCATE European Project (2010-2013)

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Abstract

The COCATE project is a three-year collaboration project under the EU 7th framework program for research. One of the objective of COCATE project is to tackle the problems of rolling out a shared transportation infrastructure capable of connecting geological storage sites with various CO₂ emitting industrial facilities. An economic model based on a dynamic linear programming system was developed, which all along the analyzed period of deployment of CO₂ network, matches the capacity left in each storage site with the CO₂ transported flow rates, in order to decide how, when and where to invest in a transport facility. The model defines in this way an optimized transport network system, with the only objective of minimizing the overall costs of CO₂ transport. Five case studies were developed leading to find a cost optimized network between 3 sources of different emission profiles, 3 sinks of different capacities, with 2 defined harbours.

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1. About network optimization in the COCATE project

Industrial CO₂ emissions are rarely located near suitable geological storage sites and there is no reason for these storage sites to be close to each other. CO₂ capture systems once invested in power plants or in industrial facilities are supposed to be operational during at least 30 - 40 years. How in this context is it possible to design ex-ante an optimized CO₂ transport network?

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When considering the deployment of a CO₂ transport network in broad geographical area, the timing of investment decisions is critical and must therefore be properly taken into account to minimize the overall costs, especially when considering the stepped deployment of CCS projects.

2. The COCATE methodology

The COCATE economic model is a dynamic linear programming system which all along the analyzed period of deployment, matches the capacity left in each storage site with the CO₂ transported flow rates, in order to decide how, when and where to invest in a transport facility. The model defines in this way an optimized transport network system, which can involve onshore and offshore pipelines as well as shipping, allowing or forbidden some of these transport systems to go through certain "nodes" (e.g. harbours, or storages) with the only objective of minimizing the total discounted costs over the project lifetime. The COCATE model could be used both by governmental institutions and group of industrials implicated in collecting and transporting their CO₂ emissions to storage sites.

COCATE economic model is developed using GAMS[®]. As shown in Fig.1, a Microsoft-Office Excel[®] interface makes it easy to any user to generate case studies and recover in an Excel[®] output file results of the model optimization.

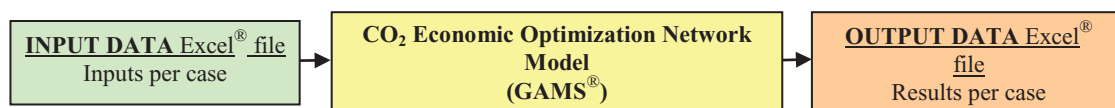


Fig. 1. Case study implementation workflow

3. COCATE Model validation

3.1. Le Havre – Rotterdam test case¹

This case allows to test the model compared to handmade results[†].

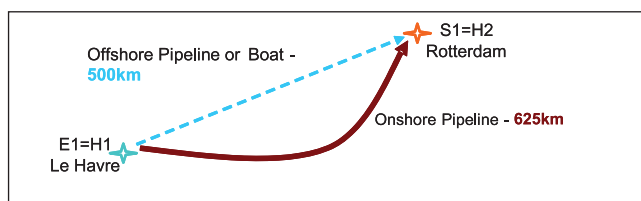


Fig. 1. Schematic of test case 1 Le Havre – Rotterdam

In the Le Havre – Rotterdam case, one emitter, "E1" (emitting 13,1 MtCO₂/year) is considered. E1 is also defined as a harbour, "H1", that should send its CO₂ to Rotterdam region, defined as a storage site ("S1" with a 1,000 MtCO₂ capacity) and as a harbour, "H2". In case 1, E1 = H1 and S1 = H2. The CO₂ is captured, transported and stored during 30 years. Five periods of six-year long are considered. The types of points (onshore and offshore storage sites, harbour, and onshore emission), their location in terms of co-ordinates, their emission / injectivity profiles and their capacity are specified by the user.

[†] In all the charts presented in the case studies, the plain arrow represents the cost optimal solution.

Rotterdam is located around 500 km away from Le Havre. In order to take into account the increase of distance when considering onshore pipeline an added distance correction coefficients between E1 and S1 is used. This distance correction was of + 25% of the distance between E1 and S1 due to factors.

3.2. Le Havre-Rotterdam cost functions test case1

COCATE model needs linear cost functions for transport and storage. In Le Havre case all costs for harbours (harbour fee and buffer storage and related ancillary equipment) are directly included in the transport cost functions. Rotterdam is considered to be a storage site in the first case. At this stage no cost is associated to this storage option. The overnight CAPEX and periodic OPEX are expressed as a function of respectively the capacity per period (peak flow rate per period) and the periodic (or average) flow rate. CAPEX and OPEX costs functions should be calculated following the annuity defined in the case.

In Le Havre - Rotterdam case, two sets of costs functions, developed on COCATE works [1], have been tested: one where the battery limits of the transport cost functions is set with an inlet pressure in Le Havre of 1 bar and another one with 150 bar. Both have an outlet pressure in Rotterdam of 200 bar (Inlet pressure of an offshore pipeline).

- Onshore pipeline cost function – Test Case 1: those cost functions are valid only for 5 periods of 6 years, for distances between 100 and 1,000 km and flow rates between 1 and 20 MtCO₂/y.

$$\text{CAPEX 150 bar (M€ overnight)} = [0.4023 + 0.0113 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{OPEX 150 bar (M€ overnight)} = [0.0531 + 0.0019 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{CAPEX 1 bar (M€ overnight)} = [0.4262 + 0.0145 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{OPEX 1 bar (M€ overnight)} = [0.0579 + 0.0126 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

- Offshore pipeline cost function – Test Case 1:

$$\text{CAPEX 150 bar (M€ overnight)} = [0.6402 + 0.0209 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{OPEX 150 bar (M€ overnight)} = [0.0337 + 0.0017 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{CAPEX 1 bar (M€ overnight)} = [0.6641 + 0.0209 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{OPEX 1 bar (M€ overnight)} = [0.0384 + 0.0124 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

- Ship cost function – Test Case 1: For ships, when considering an inlet pressure of 1bar, the liquefaction process used is ammonia cycle, whereas, when considering an inlet pressure of 150 bar, the liquefaction is done through expansion of CO₂ [2]. The outlet of the shipping transport is another harbour and the CO₂ is pumped up to 200 bar which correspond to the inlet of an offshore pipeline. Those coefficients are valid for distances between 100 and 1,000 km and flow rates between 1 and 20 Mt/y. Another cost function should be used if transport by ship directly to a storage site is considered (case 2).

$$\text{CAPEX 150 bar (M€ overnight)} = [0.2638 + 0.0048 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{OPEX 150 bar (M€ overnight)} = [0.0545 + 0.00157 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{CAPEX 1 bar (M€ overnight)} = [0.3724 + 0.0095 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

$$\text{OPEX 1 bar (M€ overnight)} = [0.0754 + 0.0218 \times \text{Peak flow rate (MtCO}_2\text{/period)}] \times \text{Distance (km)}$$

- Test Case 1.1. Onshore Pipeline option : The model is checked in terms of calculation of costs. In the case 1.1, the user forces the pipeline option. In this case there are only one emitter and one storage site. There is no optimization to do just a verification of the cost results. A 3.5 % difference in the discounted cash flows is observed with handmade calculation. The model calculates a discounted cash flow of 1,227 M€ when hand made calculates 1,271 M€.
- Test Case 1.2. Offshore Pipeline option : A 3 % difference in the discounted cash flows is observed with handmade calculation. The model calculates a discounted cash flow of 1,575 M€ when hand made calculates 1,625 M€.
- Test Case 1.3. Shipping route option : A 4 % difference in the discounted cash flows is observed with handmade calculation. The model calculates a discounted cash flow of 1,901 M€ when hand made calculates 1,815 M€.
- Test Case 1.4. No forced options: When the inlet pressure is 150 bar and there is no user's interdiction, the model selects the onshore pipeline option. This corresponds to the selection of cheapest option as seen in the different tables above. The same cost-optimized option appears when the inlet pressure is set to 1bar. When we compare this result to the one obtained by hand, the total discounted cash flows are more or less the same (difference of 1 %). The model calculates a discounted cash flow of 2,674M€ when hand made calculates 2,670M€.

Those 4 cases show that the model economic outputs are in line with cost functions. The main result is that the onshore pipeline seems to be the cost optimized option between Le Havre and Rotterdam whatever the inlet pressure.

- Test Case 1.5. Onshore pipeline cannot be built because of social acceptance issue: laying a pipeline over 625 km can be a tricky issue as far as social acceptance is concerned. The inlet pressure of the export system is 1bar. The model runs and finds out that the best option to transport CO₂ from Le Havre to Rotterdam if an onshore pipeline cannot be laid is the offshore pipeline option. The DCF of the offshore pipeline (2,682 M€) is almost equivalent to the DCF of the onshore pipeline (2,674 M€).

4. Four case studies

4.1. Case 2: Le Havre – (Rotterdam) – Offshore storage site in the North Sea

In case 2, Rotterdam is not the end destination of the CO₂ but a node to the final destination. The choice of the infrastructure will highly depend on the distance of the storage site from Le Havre and Rotterdam.

- *Case 2.1. Offshore storage site in the North Sea 450 km away from Le Havre: in this case, COCATE model finds the cost optimized option is the ship option from H1 Le Havre directly to S1 the offshore storage.*

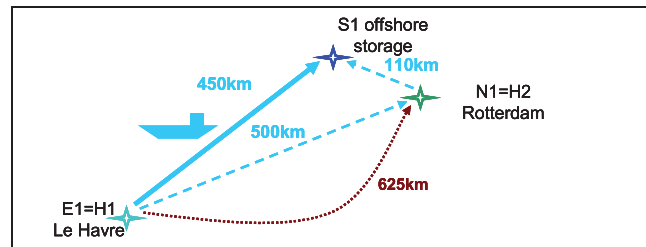


Fig. 2. Schematic of Case 2.1 - Le Havre – (Rotterdam) – Offshore Storage (firm line is the option chosen by COCATE model)

Table 6. Results of the model – Case 2.1

	CAPEX overnight (M€)	OPEX (M€/y)	Total undiscounted costs (M€)	DCF (M€)	Equivalent transport cost (€/disc/t _{disc})
Model results	556	177	5,824	2,352	14.7

The costs obtained here are smaller than in case 1.5 (where offshore pipeline is cheapest solution between ship and offshore pipeline) as the distance to the offshore storage site is smaller than the one to Rotterdam and as no additional buffer storage cost or fees was considered.

- *Case 2.2. Offshore storage site in the North Sea 600 km away from Le Havre:*

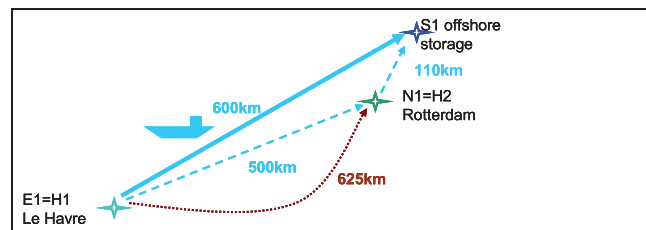


Fig. 3. Schematic of Case 2.2 - Le Havre – (Rotterdam) – Offshore Storage

Table 7. Results of the model – Case 2.1. The cost optimized option is the ship.

	CAPEX overnight (M€)	OPEX (M€/y)	Total undiscounted costs (M€)	DCF (M€)	Equivalent transport cost (€/disc/t _{disc})
Model results	745	213	7,077	3,147	19.7

If the ship option is excluded from the choice and then the onshore pipeline option to Rotterdam and the offshore pipeline from Rotterdam to the offshore storage site is the second best and is 5% more expensive than the ship option.

4.2. Case 3: Le Havre – (Rotterdam) – Offshore storage site in the North Sea and Onshore storage site in Paris Basin (firm line is the option chosen by COCATE model)

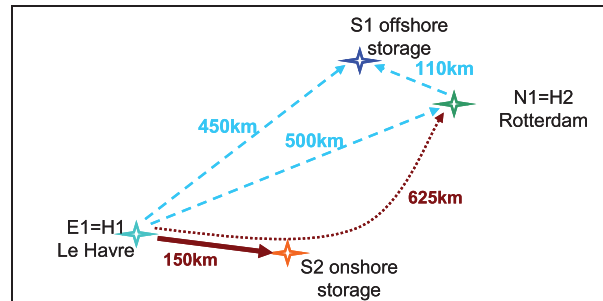


Fig. 4. Schematic of Case 3 - Le Havre – (Rotterdam) – Offshore Storage in the North Sea – Onshore storage site in Paris Basin

As we did not put any constraint on capacity and on costs for the onshore storage solution 150 km away from Le Havre, the model chooses obviously the closest storage solution, S2 with an onshore pipeline.

Table 8. Results of the model – Case 3.

	CAPEX overnight (M€)	OPEX (M€/y)	Total undiscounted costs (M€)	DCF (M€)	Equivalent transport cost ($\text{€}_{\text{disc}}/\text{t}_{\text{disc}}$)
Model results	266	34	1,102	647	4.4

4.3. Case 4: Le Havre + Other emitters to an offshore storage site in the North Sea and an onshore storage site in Paris Basin

- Case 4.1. Le Havre + Rotterdam to an offshore storage site in the North Sea and an onshore storage site in Paris Basin:

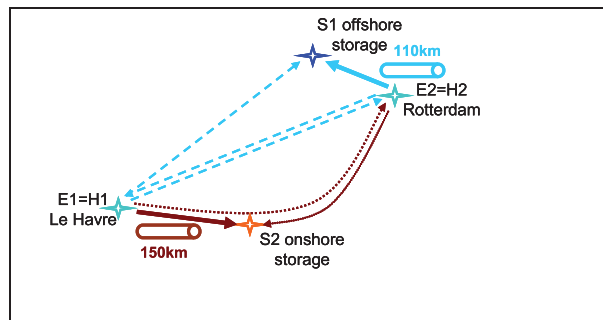


Fig. 5. Schematic of Case 4.1 - Le Havre + Rotterdam – Offshore Storage in the North Sea – Onshore storage site in Paris Basin

Table 9. Results of the model – Case 4.1

	CAPEX overnight (M€)	OPEX (M€/y)	Total undiscounted costs (M€)	DCF (M€)	Equivalent transport cost ($\text{€}_{\text{disc}}/\text{t}_{\text{disc}}$)
Model results – all infrastructures	603	64	2,106	1,324	3.9
<i>E1 to S2 – onshore pipeline 13.1MtCO₂/y – 150km</i>	266	34	1,102	647	4.4
<i>E2 to S1 – offshore pipeline 17MtCO₂/y – 110km</i>	337	30	1,004	677	3.5

- Case 4.2. Le Havre +Rotterdam +E3 to an offshore storage site in the North Sea and an onshore storage site in Paris Basin

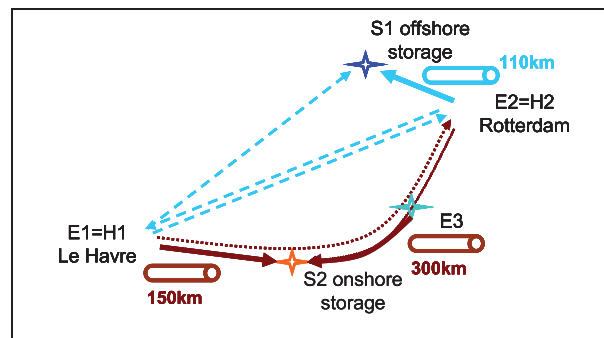


Fig. 6. Schematic of Case 4.2 - Le Havre + Rotterdam+E3 – Offshore Storage in the North Sea – Onshore storage site in Paris Basin

The presence of E3 does not affect the previous infrastructure as an onshore pipeline is built from E3 to S2.

Table 10. Results of the model – Case 4.2

	CAPEX overnight (M€)	OPEX (M€/y)	Total undiscounted costs (M€)	DCF (M€)	Equivalent transport cost ($\text{€}_{\text{disc}}/\text{t}_{\text{disc}}$)
Model results – all infrastructures	992	116	3,783	2,305	5.1
<i>E1 to S2 – onshore pipeline 13.1MtCO₂/y – 150km</i>	266	34	1,102	647	4.4
<i>E2 to S1 – offshore pipeline 17MtCO₂/y – 110km</i>	337	30	1,004	677	3.5
<i>E3 to S2 – onshore pipeline 10MtCO₂/y – 300km</i>	389	52	1,677	981	8.7

4.4. Case 5: 3 emitters – 3 storage sites

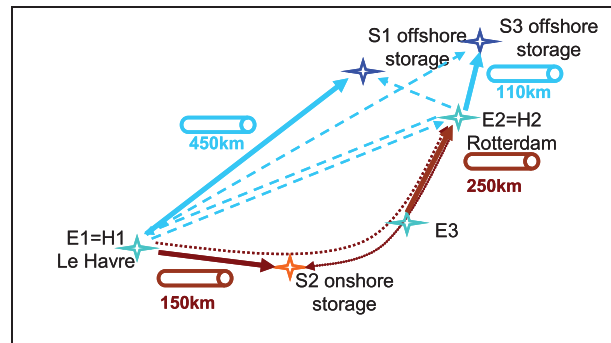


Fig. 7. Schematic of Case 5 - Schematic of Case 5 - Le Havre + Rotterdam+E3 – 2 Offshore Storage sites in the North Sea – Onshore storage site in Paris Basin – S2 Limited Capacity

Table 10. Results of the model – Case 5

	CAPEX overnight (M€)	OPEX (M€/y)	Total undiscounted costs (M€)	DCF (M€)	Equivalent transport cost (€/disc/t _{disc})
Model results – all infrastructures	1,930	168	5,631	3,824	8.5
<i>E1 to S2 – onshore pipeline – 5MtCO₂/y – 150km</i>	<i>129</i>	<i>14</i>	<i>461</i>	<i>288</i>	<i>5.1</i>
<i>E1 to S1 – offshore pipeline 8.1MtCO₂/y – 450km</i>	<i>977</i>	<i>62</i>	<i>2,161</i>	<i>1,676</i>	<i>18.4</i>
<i>E3 to H2/S2 – onshore pipeline 10MtCO₂/y – 250km</i>	<i>324</i>	<i>44</i>	<i>1,410</i>	<i>817</i>	<i>7.3</i>
<i>E3+E2 to S3 – offshore pipeline 27MtCO₂/y – 110km[‡]</i>	<i>500</i>	<i>48</i>	<i>1,599</i>	<i>1,043</i>	<i>3.4</i>

Here we have just considered one period and S2 has a limited storage capacity. If we had considered several periods, the model would maybe have chosen to develop S2 during the first period and to build a bigger pipeline to S2 during this period.

[‡] The cost functions used in this case should give reasonable costs for offshore pipeline from 5 to 30MtCO₂/y.

5. Conclusion

The COCATE economic model was applied to Le Havre case and have developed step by step a multisources/multisinks case. Five cases were developed. Through the first case we were able to test the model in terms of economic results.

The model confirms that between Le Havre and Rotterdam, for 13.1 MtCO₂/y transported, onshore pipeline was the cheapest solution, which is in line with handmade results. However with the second case, we noticed that if we wanted to store this same flow rate of CO₂ in an offshore storage site located 450 or 600 km away from Le Havre but around 100 km away from Rotterdam, the best cost wise choice was ship from Le Havre directly to the storage site.

The third and fourth cases were dedicated to test the model robustness through handling additional storage sites and additional emitters. Finally with the 5th case, we managed to find a cost optimized network between 3 sources of different emission profiles, 3 sinks of different capacities, with 2 harbours defined. Through the model we were able to find this cost optimized network solution really quickly (around one hour of calculation time).

COCATE model needs to have very accurate cost functions of all the possible options around the emitter and around the storage site. The results is highly dependant on these cost functions which are very sensitive to the coefficients given by the user. The run time increases when the number of periods, of emitters, of storage sites increases, when the emission profiles from one emitter to another are not from the same order of magnitude, when the discounted cash flows of 2 options are really close from each another. The more the cost functions data base available to the model is large the more the result of the optimization is accurate. Further improvements to the COCATE model on this issue is required to be able to face a large range of possible case studies.

In addition, only the costs were here optimized while for more advanced investment decisions more parameters, such as, financial risk, environmental impact, social acceptance, risks, shall be taken into account [3-5].

Acknowledgements

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